NATION WIDE ^{222}Rn AND ^{220}Rn ATLAS FOR INDIA

T.V. Ramachandan[1], L.A. Sathish[2*] and S. Sundareshan[3]

[1]Ex-Environmental Assessment Division, Bhabha Atomic Research Center, Mumbai- 450 085, India
[2]Department of Physics, Government Science College, Bangalore – 560 001, India
[3]Department of Physics, Vijaya College, Bangalore – 560 004, India

*Corresponding Author (Sathish) Email: lasgayit@yahoo.com

Abstract

Considering the epidemiological effect of radon on human beings, an attempt is made to make a nation-wide atlas of ^{222}Rn and ^{220}Rn for India. More than 5000 measurements have been carried out in 1500 dwellings across the country, India. The solid state nuclear track detectors were deployed for the measurement of indoor ^{222}Rn, ^{220}Rn and their progeny levels. The mean annual inhalation dose rate due to ^{222}Rn, ^{220}Rn and their progeny in the dwellings is found to be 0.97 mSv y^{1} (GSD 2.49). It is observed that the major contribution to the indoor inhalation dose is due to ^{222}Rn and its progeny. However, the contribution due to ^{220}Rn and its progeny is not trivial as it is about 20% of the total indoor inhalation dose rates. The dependence of indoor ^{222}Rn levels in dwellings has shown a significant difference between the nature of walls and floorings. The results are discussed in detail.

Key words: ^{222}Rn, ^{220}Rn, inhalation, radiation doses.

Corresponding Author:
Dr.Sathish.L.A
Assistant Professor
Department of Physics
Government Science College
Nrupathunga Road,
Bangalore – 560 001
India
+91-80-9886639324

Introduction

Ever since studies on uranium miners established the presence of a positive risk coefficient for the occurrence of lung cancer in miners exposed to elevated levels of ^{222}Rn and its progeny, there has been a great upsurge of interest in programmes concerned with the measurement of radon in the environment. This interest was accentuated by the observations of elevated radon levels in the indoor environment in many countries that led to the realization of residential radon as being a possible public health issue in the western world. It was also hoped that in conjunction with epidemiological studies, large-scale indoor ^{222}Rn surveys might lead to quantitative understanding of the low dose effects of ^{222}Rn exposures. As a result of these, considerable amount of information is available on the levels of ^{222}Rn gas and its progeny in the indoor environment across the globe (UNSCEAR, 2000)**.** In contrast, there exist a few studies relating to the measurements of ^{220}Rn in the environment **(**Doi and Kobayashi 1994; Doi et al, 1994) since it is assumed that the inhalation dose to the general population from ^{220}Rn and its progeny is only about 10% of the inhalation dose due to ^{222}Rn (UNSCEAR, 2000)**.** But, recent studies in many countries have revealed that this assumption if far from the truth (Steinhausler et al, 1994)**.** In general, such studies are important in two ways. Firstly, any radiological impact assessment of nuclear facilities, either existing or those to be set up in the future, requires information on the exposure due to natural radiation prevalent in their vicinity. Secondly, the radiation risk coefficients are fairly well established at high doses and high dose rates, whereas little is known about the effects of radiation at low dose rates. Several epidemiological study programmes in different countries are in progress to estimate the population exposures due to natural radiation with a view to obtain the radiation risk coefficients at low dose rate levels. In this regard, radiation surveys in high background areas will provide an excellent setting for epidemiological studies relating to the effects of low doses of radiation. In view of these, a comprehensive estimate of the natural inhalation dose requires both ^{222}Rn and ^{220}Rn levels in the indoor and outdoor atmosphere.

Sources of ^{222}Rn and ^{220}Rn

Radionuclides such as ^{222}Rn and ^{220}Rn, from the uranium and thorium decay chains are noble gases produced by the decay of their immediate respective parent nuclides, ^{226}Ra and ^{224}Ra, present in natural rocks, uranium ores and soils (Fleischer, 1997)**.** The decay products of ^{222}Rn and ^{220}Rn are the radioactive isotopes of polonium, bismuth, lead and thallium. ^{222}Rn decay products are divided into two groups; the short-lived ^{222}Rn daughters such as ^{218}Po

(RaA), ^{214}Pb (RaB), ^{214}Bi (RaC), ^{214}Po (RaC^{1}) with half-lives below 30 min, and long-lived ^{222}Rn decay products such as ^{210}Pb (RaD), Bi (RaE), ^{210}Po (RaF). However, ^{220}Rn progeny has no long-lived group. Most important radionuclide in this chain is the lead isotope ^{212}Pb with a half-life of 10.6 h. These daughter products, being the isotopes of heavy metals, get attached to the existing aerosols, suspended particulate matters, in the atmosphere. Their elimination from the atmosphere occurs either by radioactive decay or by other removal processes such as plate-out or surface deposition and washout by rain. Vast differences in the half-lives of ^{222}Rn (3.8 d) and ^{220}Rn (55 s) is a crucial parameter in governing their release from the ground and subsequent distribution in the free atmosphere. When radium decays in soil grains, the resulting atoms of ^{222}Rn isotopes first escape from the mineral grains to air-filled pores. The fraction of ^{222}Rn escapes into the pores is known as the emanation power fraction. Even though the detailed processes responsible for ^{222}Rn emanation from grains are not fully understood, it is believed that the main contribution to the emanation comes from the recoil processes (Nazaroff, 1988)**.** The recoil range is about 0.04 - 0.06 μm in grain materials and about 60 μm in air (Tanner, 1980)**.** Also, recoil-stopping distance of ^{222}Rn and ^{220}Rn is lower in water than in air. Hence, the moisture content influences the emanation power fraction (Megumi and Mamuro, 1974; Strong and Levins, 1982; Ingersall, 1983; Stranden et al, 1984)**.** Emanation power fraction of building materials for ^{220}Rn is about 2-10 times smaller than that for ^{222}Rn, despite the greater recoil energy of ^{220}Rn atoms (Porstendorfer, 1994)**.** Experimental studies on building show that it ranges from 0.2 to 30% for ^{222}Rn and 0.2 to 6% for ^{220}Rn (Porstendorfer, 1994; Barretto et al, 1972)**.** Transport of ^{222}Rn through the soil takes place by diffusion and/or with gases like CO_2 and CH_4 or water moving in the soil horizons. The diffusion coefficient for ^{222}Rn in different soil types varies from 10^{-9} to 10^{-5} m^2 s^{-1} from water to air media (UNSCEAR, 1992)**.** ^{222}Rn and ^{220}Rn enter the atmosphere mainly by crossing the soil-air or building material-air interface. Typical values of exhalation rate (amount of activity released per unit area of the surface per unit time) for ^{222}Rn in soil and building material are 0.02 and 5.0×10^{-4} Bqm^2s^{-1}, respectively. The same for ^{220}Rn are as high as 1 and 0.05 $Bqm^{-2}s^{1}$, respectively (Porstendorfer, 1994)**.** ^{222}Rn and ^{220}Rn progeny aerosols in the atmosphere are generated in two steps. After the formation from the ^{222}Rn isotope by decay, the freshly generated radionuclides react very fast with trace gases and air vapors, and become small particles, called clusters or unattached radionuclides with diameters varying from 0.5 to 5 nm. In addition, these radionuclides attach to the existing aerosol particles in the atmosphere within 1 - 100s, forming the radioactive aerosols. Most of the newly formed decay product clusters are positively charged and have a high mobility

(Porstendorfer and Mercer, 1979). Mobility is characterized by the diffusion coefficient that mainly controls the formation of the radioactive aerosol by attachment and their deposition on surfaces and in the human lung.

^{222}Rn and ^{220}Rn in indoor environments mainly originate from emanation of the gases from the walls, floor and ceilings. Most terrestrial building materials have 3-4 orders of magnitude higher gas concentrations in pore spaces than in the atmosphere, permanently maintained by the continuous decay of its parent nuclides. High concentration leads to a large ^{222}Rn /^{220}Rn gradient between the materials and open air. Levels of ^{222}Rn and ^{220}Rn in the open atmosphere are governed by the balance between the exhalation rate and the atmospheric dilution processes.

The external gamma dose rates have been more or less well mapped in India by several studies. A countrywide survey of outdoor natural gamma radiation levels using Thermo Luminescent Dosimeters (TLD) covering quite large number of locations scattered all over the country revealed that the average external gamma radiation dose for the country is about 775 μGy yr^{-1} (Nambi et al, 1986). Mishra and Sadasivan (1971) have projected a national average value of 707 μGy yr^{-1} based on natural radioactivity analysis of undisturbed soil samples from more than 30 different locations, all over the country, assuming a uniform cosmic ray component of 287 μGy yr^{-1}. Of the terrestrial component, 48.7% of the contribution is from ^{40}K and the remainder is by the thorium (33.6%) and uranium series (17.7%) (Sadasivan et al, 2003). Tables 1 and 2 give the estimated natural radioactivity content in the building materials used for construction in India and the distribution of ^{238}U and ^{232}Th in Indian soil (Sadasivan et al, 2003). It can be seen from these tables that ^{40}K is also a major source of radiation in the environment. A good database on the countrywide concentration levels of ^{238}U, ^{232}Th and ^{40}K in geological materials as shown in Table 3 (Sankaran et al, 1986). Table 4 gives the estimated ranges of ^{222}Rn entry rate from different sources in typical houses (ICRP, 1986). It is evident that soil has the highest entry rates followed by brick or concrete.

Environmental measurements of ^{222}Rn were mostly confined to outdoor atmospheric air earlier. Since 1970, indoor ^{222}Rn levels were measured with keen interest, and several large-scale surveys have been carried out by several agencies all over the world (Campos-Venuti et al, 1994; UNSCEAR, 2000). Typical worldwide indoor and outdoor levels of ^{222}Rn are about 45 and 7 Bq m^{-3}, respectively and that of outdoor ^{220}Rn level is estimated as 0.2 Bq m^{-3}

(Mettler and Upton, 1995). An initial survey in Indian houses indicates that the indoor ^{222}Rn concentration varied between 2.2 to 56 Bq m^{-3} with a geometric mean of 15.1 Bq m^{-3} (Subba Ramu et al, 1993). The reported indoor ^{222}Rn and ^{220}Rn levels are tabulated in Tables 5 and 6 respectively, shows that the population weighted worldwide average ^{222}Rn concentration is 39 Bq m^{-3}; while the geometric mean calculated for the data is 30 Bq m^{-3} with a geometric standard deviation of 2.3 (UNSCEAR, 2000). Average equilibrium equivalent concentration of ^{220}Rn (Table 6) range between 0.2 and 12 Bq m^{-3}, while the ratio of ^{222}Rn/^{220}Rn EEC varied from 0.01 to 0.5 worldwide. All this information facilitated the understanding of many environmental processes, which affect the distribution of ^{222}Rn and ^{220}Rn levels in indoors and outdoors and the related radiation exposure to man. However, there exist still many problems associated with the accurate assessment of exposures and radiation doses to general population due to ^{222}Rn, ^{220}Rn and their progeny.

Measurement Methodology

The present national survey covered 25 locations. About 1500 houses of different types of construction were surveyed on a time integrated quarterly cycle of 90 days covering all the four seasons of a calendar year. Solid State Nuclear Track Detector (SSNTD) based dosimeters (Nikolaeve and Ilic, 1999; Subba Ramu et al, 1994) were used for the survey. These are simple to use and less expensive as compared to some continuous measurement systems like the AlphaGuard. The latter is useful for occasional comparisons with the SSNTD based dosimeters. In view of this, SSNTD based dosimeters, described in the following section, were developed and calibrated for the national survey. Since the sampling is passive and integrated for long duration, the diurnal and seasonal variations in radon concentrations are being taken into account (Ilic and Suteg, 1997).

SSNTD based dosimeter System developed is a cylindrical plastic chamber divided into two equal compartments (Nambi et al, 1994), each having an inner volume of 135 cm^3 and height 4.5 cm. Dimensions of the dosimeter are chosen based on the ratio of the effective volume of the cup to its total volume to achieve maximum track registration for the cylindrical cup (Jha et al, 1982). The design of the dosimeter is well suited to discriminate ^{222}Rn and ^{220}Rn in mixed field situations, where both the gases are present as in the monazite deposited areas. Cellulose nitrate films of LR-115 type II manufactured by the Kodak Pathe are used as detectors. The 12 μm thick film cut into 2.5 cm × 2.5 cm size is affixed at the bottom of each cup as well as on the outer surface of the dosimeter. The exposure of the detector inside the

cup is termed as cup mode and the one exposed open is termed as the bare mode. One of the cups has its entry covered with a glass fiber filter paper that permeates both ^{222}Rn and ^{220}Rn gases into the cup and is called the filter cup. The other cup is covered with a semi-permeable membrane (Ward et al, 1977) sandwiched between two-glass fiber filter papers and is called the membrane cup. This membrane has permeability constant in the range of 10^{-8} -10^{-7} cm^2s^{-1} (Wafaa, 2002) and allow more than 95 % of the ^{222}Rn gas to diffuse while it suppress the entry of ^{220}Rn gas almost completely. Thus, the SSNTD film inside the membrane cup registers tracks contributed by ^{222}Rn only, while that in the filter cup records tracks due to ^{222}Rn and ^{220}Rn. The third SSNTD film exposed in the bare mode registers alpha tracks contributed by the concentrations of both the gases and their alpha emitting progeny.

The dosimeter is kept at a height of 1.5 m from the ground and care is taken to keep the bare card at least 10 cm away from any surface. This ensures that errors due to tracks from deposited activity from nearby surfaces are avoided, since the ranges of alpha particles from ^{222}Rn /^{220}Rn progeny fall within 10 cm distance. After the exposure period of 90 days, the SSNTD films are retrieved and chemically etched in 2.5 N NaOH solutions at 60 °C for 60 minutes with mild agitation throughout (Miles, 1997)**.** The tracks recorded in all the three SSNTD films are counted using a spark counter. A methodology has been developed to derive the equilibrium factors separately for ^{222}Rn and ^{220}Rn using the track densities based on the ventilation rates in the dwellings (Mayya et al, 1998)**.**One may expect deposition of activity on the SSNTD film in the bare mode exposure, which may pose as an unknown parameter in the calibration factor. But it has been proved that the LR-115 (12 μm) film does not register tracks from deposited activity (Eappen et al, 2004)**.** This is because the E_{max} for LR-115 film is 4 MeV and all the progeny isotopes of ^{222}Rn /^{220}Rn emit alphas with energies greater than 5 MeV.

Calibration Facility and Standardization of Dosimeter

Experiments were carried out at the Bhabha Atomic Research Centre, Mumbai, India to estimate the calibration factors (Ramachandran et al, 1995) separately for ^{222}Rn and ^{220}Rn, in a calibration chamber of stainless steel of 0.5 m^3 volume. ^{222}Rn (or ^{220}Rn) gas is introduced into the chamber from standard sources obtained from Pylon, Canada. The calibration chamber has provisions for imputing aerosols from an aerosol generator, which is a Sinclair LaMer type condensation aerosol generator. It gives a laminar flow of mono-dispersed aerosols of di-2-ethylhexyl sebacate condensed on NaCl nuclei**.** The temperature settings of the boiler and re-heater are adjusted to obtain mono-dispersed aerosols of 0.25 μm diameter,

which is close to the activity median aerodynamic diameter of 0.2 |µm reported for indoor aerosols (Yihe et al, 1996). Aerosol concentrations of the order of 10^4 to $I0^5$ particles per cm^3 of air were generated to simulate the indoor environment conditions. Depletion of the aerosols inside the chamber was studied and accordingly input of the aerosols was regulated to maintain a near constant particle concentrations. The chamber has provisions for coupling an on-line Lucas cell system in conjunction with an AlphaGuard for continuous measurement of ^{222}Rn gas concentration. The AlphaGuard, kept inside the chamber recorded hourly averaged ^{222}Rn concentrations. The on-line Lucas cell system was coupled to an alpha counting setup and counts were taken synchronizing with the timing of the AlphaGuard.

The comparison of ^{222}Rn measured by the two systems for a wide range of concentrations showed very good correlation of regression coefficient 0.97 and has a slope equal to unity (Eappen et al, 2001). Calibration factors (concentration conversion factors) for ^{222}Rn and ^{220}Rn are required to convert the recorded tracks in the exposed SSNTD films into ^{222}Rn and ^{220}Rn concentrations. Calibration factors were estimated experimentally as well as theoretically for all the three modes of exposures. These are discussed in the following sections.

Calibration factors (CFs) for ^{222}Rn and ^{220}Rn gases in the cup mode were determined through a series of experiments. CFs for ^{222}Rn (k_R) and for ^{220}Rn (k_T) in terms of tr cm^{-2} per Bq d m^{-3} can be obtained as:

$$k_R = \frac{24T}{C_R H} \quad and \quad k_T = \frac{24T}{C_T H}$$

where, T is the tracks per unit area (tr cm^{-2}), C_R is concentration of the ^{222}Rn gas (Bq m^{-3}), C_T is the level of ^{220}Rn gas (Bq m^{-3}) and H is the exposure time (hours). Experimentally obtained calibration factors for ^{222}Rn and ^{220}Rn are given in Table 7 for cup mode exposure. CF for ^{222}Rn in the membrane compartment is found to be equal (0.019 tr cm^{-2} / Bq d m^{-3}) to that in filter paper compartment (0.02 tr cm^{-2}/Bq d m^{-3}). CF for ^{220}Rn in the membrane cup is essentially zero and that in the filter paper cup is 0.017 tr cm^{-2}/Bq d m^{-3}. The definition of the CF for the bare mode has certain ambiguities. In the earlier approach, the CF for the bare detector was defined as the track density rate obtained per unit WL (Barillion and Chambraudet, 2000; Durrani and Ilic, 1997). In reality, track formation rate in the bare mode is not a unique function of WL, but would depend on the equilibrium factor (F). If one defines the bare detector calibration factor as k_B (tr cm^{-2}/Bq d m^{-3}) of each species, it may be easy to show that this quantity is independent of the equilibrium factor as well as the

incident energy of the alpha particle. For a given track density rate 7(tr cm^{-2} d^{-1}) and working level (W_R for ^{222}Rn and W_T for ^{220}Rn in mWL units) and the corresponding equilibrium factors, F_R and F_T, the calibration factors as defined above can be obtained for ^{222}Rn (k_{BR}) and ^{220}Rn (k_{BT}) respectively in terms of tr cm^{-2} / Bq d m^{-3} using the following equations.

$$k_{BR} = \left(\frac{T}{3.7W_R}\right)\left(\frac{F_R}{1+2F_R}\right)$$

$$k_{BT} = \left(\frac{T}{0.275W_r}\right)\left(\frac{F_T}{2+F_r}\right)$$

Based on this concept CFs was derived for the species matrix for ^{222}Rn, ^{220}Rn and their progeny concentrations. They were found to be nearly constant for a wide range of equilibrium factors (0.1 - 0.72) supporting the basic assumption of the new approach. Table 7 shows the results of the CFs for the bare mode exposure for ^{222}Rn and ^{220}Rn. The CF for ^{222}Rn and ^{220}Rn are estimated as 0.02 tr cm^{-2}/Bq d $m^{-3}$and 0.019 tr cm^{-2}/Bq d m^{-3}, respectively and are nearly identical. This confirms the assumption that the bare card calibration factors are the same for the alpha emitters since they are functions of only the difference in the ranges and the lower and upper cut off energies of the detector. Hence for practical use, an average value of 0.02 tr cm^{-2}/Bq d m^{-3}may be used as the CF for ^{222}Rn and ^{220}Rn in the bare mode exposure. A Theoretical model has been developed to derive the calibration factors for ^{222}Rn and ^{220}Rn for all the exposure modes (Eappen and Mayya, 2004)**.** The theoretical model is based on certain parametric constants chosen after experimental verifications. These include the bulk-etching rate and the break down thickness for the spark counting technique. The present calculation uses bulk etching rate as 4.0 µm/h and break down thickness as 3.0 µm**.** In the model, the upper and lower cut off energies for normal incident alphas are translated as residual ranges using the range energy relationship. The sphere of influence for the upper and lower cut off energies from normal incident angle to critical angle can be obtained from integrating for the total area covered under solid angle for residual length of alpha particles lying within those incident angles. With these considerations, the observable tracks per unit area on the film per unit exposure time can be computed using the following equation.

$$T_r = \frac{\eta c}{4\pi}\int_0^{2\pi} d\phi \int_{\theta=0}^{\theta_c} d\theta \int_{r=R_E-R_L(\theta)}^{R_F-R_U} \sin\theta\cos\theta dr$$

where η is the efficiency of track registration, C is the activity concentration of the species,ϕ is the solid angle suspending the area of influence, θ is the angle of incidence ranging from normal incidence (0°) to critical angle (θ_C), r is the radial distance from the point of emission, R_E is the range of the alpha particle corresponding to its max energy and R_L, R_U are the lower and upper cut off ranges for track registration for an incident angle θ The integration extends over a region of influence, which is constructed by using detailed track development model. Eappen et al (2004) have discussed the typical regions of influence for ^{222}Rn and ^{220}Rn and their progenies in bare mode exposure configuration. Authors have showed that the region of influence is located farther from the detector for ^{220}Rn progeny as compared to ^{222}Rn and its progeny concentrations. For the cup mode exposure, integrations over the regions of influence would also include surface deposited activity contributions from the inner walls of the dosimeter.

A code has been written in FORTRAN for calculating the calibration factors in different configurations using the theoretical model (Eappen et al, 2001)**.** Several experimental studies were carried out in the calibration facility to determine the calibration factors under various equilibrium factor and gas concentration conditions. Theoretical and the experimental CFs obtained for the cup mode and bare mode exposures show close agreement with each other.

Dosimetric Methodology

Inter-laboratory standardization experiments for the etching characteristics conducted by all the participants using standard alpha source also showed good agreements. A theoretical methodology has been developed for evaluating the progeny concentrations using the twin cup ^{222}Rn - ^{220}Rn dosimeter system (Mayya et al, 1998)**.** The mathematical basis used is similar to that developed by Planinic and Faj (1990, 1991) for radon dosimetry in which an auxiliary parameter, ventilation rate, was extracted from the equations relating the bare detector track densities to the gas and progeny levels. This approach is considered as most logical one for ^{222}Rn - ^{220}Rn dosimetry with bare and cup detector system. But this methodology is complicated in the mixed field situation by the fact that ^{220}Rn contribution has to be given as its ventilation dependant spatial profile for which only limited information is available in literature. So the data currently available in the literature are used for the parameters like wall loss rates, unattached fractions and indoor turbulence levels (Porstendorfer, 1994)**.** In this method, it is assumed that SSNTD kept in the bare mode responds only to the airborne alpha emitters and not to the alpha activity deposited on it. It is also assumed that the bare card calibration factors are same for alpha emitters since it is a

function of only the difference in the ranges, lower and upper cut off energy of the detector. Let T_1, T_2 and T_3 be the track densities recorded in the membrane mode, filter mode and bare mode, respectively. Let and k_R be the calibration factors for ^{222}Rn gas in membrane compartment and filter compartment, respectively and k_T be the calibration factor for ^{220}Rn in the filter compartment. If d is the duration of exposure (days), the gas concentrations of ^{222}Rn (Bq m^{-3}) and ^{220}Rn (Bq m^{-3}) the vicinity of the dosimeter can be determined from the observed track densities T_1 and T_2 using the following equations:

$$C_R = \frac{T_1}{dk_R} \quad and \quad C_T = \frac{T_2 - dC_R k_R}{dk_T}$$

Since the ^{222}Rn decay constant is far smaller than the usually encountered air change rates (ventilation rates), ^{220}Rn may be assumed to be spatially uniform. The activity fractions of the progeny are governed by their wall loss rates for the fine and the coarse fractions and the ventilation rates. The bare track densities are also dependent on the ventilation rates, which represent the progeny fractions for both gases. However unlike ^{222}Rn, ^{220}Rn is not uniformly distributed in the room due to its short half-life, but is expected to set up profiles (Doi and Kobayashi, 1994)**.** The concentration C_T would be considerably lower than that present near the ground and the walls, which are the ^{220}Rn emitting surfaces. On the other hand, the thoron decay products, ^{212}Pb and ^{212}Bi, being longer lived would mix more or less uniformly in the room and their activities will be fractions of a representative average ^{220}Rn concentration. A turbulent-diffusive transport model developed by Mayya et al, (1998) was used to obtain the bare track densities in terms of this concentration and the indoor ventilation rates. This method, which is known as the root finding method (RFM), is theoretically the most satisfactory approach for determining ^{222}Rn, ^{220}Rn concentrations and their progeny working levels using the tracks recorded on the three SSNTD films. The progeny working levels were evaluated using the following relations:

$$WL_R = \frac{C_R F_R}{3700} = \frac{C_R(0.104F_{RA} + 0.518F_{RB} + 0.37F_{RC})}{3700}$$

$$WL_T = \frac{C_T F_T}{275} = \frac{C_T(0.908F_{TB} + 0.092F_{TC})}{275}$$

where F_R and F_T are the equilibrium factors for ^{222}Rn and ^{220}Rn progeny, respectively, which are related to the ventilation rate. However, in practice, it was found that small uncertainties in the recorded tracks propagate non-linearly leading occasionally to unacceptable solutions for the equilibrium factors. Very rich experience in measurements is required to eliminate

these uncertainties, which is expected to be realized in the coming few years. Until then, it was decided to estimate the progeny concentrations using the cup based gas concentrations and the universally accepted equilibrium factors published elsewhere (UNSCEAR, 2000). Information obtained from the third SSNTD is being used in conjunction with the RFM for building a database on the equilibrium factors. At present, the effective dose rate due to inhalation was estimated from the ^{222}Rn, ^{220}Rn and progeny concentrations using the UNSCEAR (2000) equilibrium factors as given in Table 8.

Inhalation Dose

Absorbed dose rates to the critical cells of the respiratory tract due to ^{222}Rn, ^{220}Rn and their progeny can be estimated on the basis of aerosol characteristics, its size distribution, unattached fraction, breathing fraction, and fractional deposition in the airways, mucous clearance rate and location of the target cells in the airways. Several models have been developed to assess the inhalation dose rates to the population due to ^{222}Rn, ^{220}Rn and their progeny (Jacobi, 1993; Subba Ramu, 1988). Lung dose distribution assessment carried out by different agencies from the year 1956 to 2000 show a large variation in dose conversion factors (UNSCEAR, 1993, 2000). The estimated dose conversion factors varied drastically based on the breathing rate as well as the target tissue mass. In the present study, the dose conversion factors reported by UNSCEAR (2000) have been used to estimate the indoor inhalation dose rates D (μSvh^{-1}) due to ^{222}Rn, ^{220}Rn and their progeny as shown below:

$$D = 10^{-3}[(0.17 + 9F_R)C_R + (0.11 + 40F_T)C_T]$$

Numerical values given in the above relations are the dose conversion factors for gas and progeny concentrations.

Results and Discussion

Present survey covers 25 locations in different parts of the country. This database alone was not sufficient for obtaining a comprehensive mean value of the indoor ^{222}Rn and ^{220}Rn levels on a national scale. Hence, similar data generated and published by this centre as well as published by several groups elsewhere have also been used for the purpose. This data includes mainly the indoor ^{222}Rn levels and the equilibrium factors estimated earlier survey using single cup dosimeter covering more than 90 locations (UNSCEAR, 1993) and the data generated from the survey carried out around 12 nuclear installations in India using the twin chamber ^{222}Rn /^{220}Rn dosimeters (Ramachandran et al, 1995). In the case of ^{220}Rn, the data

generated from 25 locations under this study and the data generated from the survey carried out around nuclear installations in India were used.

Indoor ^{222}Rn and ^{220}Rn Level

Estimated levels of indoor ^{222}Rn and the equilibrium factors between ^{222}Rn and its progeny in 105 houses of different types of construction at 84 locations in different parts of India by the single cup method are given in Table 9. The estimated ^{222}Rn level at different locations varies from 6.4 Bqm^{-3} to 95.4 Bq m^{-3} with a geometric mean of 25.5 Bq m^{-3} (GSD 2.1). Equilibrium factors were estimated using the bare detector exposure mode along with the cup with membrane mode in these locations for ^{222}Rn progeny. From the calibration factors for the bare detector, the progeny concentrations are evaluated and the equilibrium factors were estimated using the standard equation. Equilibrium factors for ^{222}Rn progeny range between 0.21 and 0.95 (UNSCEAR, 1993) with a geometric mean of 0.54 (GSD 1.4). Estimated mean equilibrium factors range between 0.1 and 0.9, but most of the values are found to be within 30% of the typical value of 0.4 used by the UNSCEAR (1993) for inhalation dose calculations**.** Values thus computed using the standard relation is not strictly correct, since the bare detector exposure is not a function of WL, but depends on the F factor.

A theoretical methodology has been developed incorporating this fact to extract the modified F values. Using this concept, the revised F values were evaluated and these values are found to vary from 0.12 to 1.2 with a median of 0.46 ± 0.2. Although, the median value of F is found to decrease in the revised estimates, the spread is found to be higher. Besides, the distribution is found to be skewed to the left, unlike the near symmetrical form shown by the pre-revised data in Fig.1. Mathematical analysis of the ***F*** distribution shows that the ***F*** values correspond to a mean ventilation rate of 2 per hour with a GSD of 3 (UNSCEAR, 1988)**.**

Results on the indoor ^{222}Rn, ^{220}Rn levels and the estimated inhalation dose rates are presented in Table 10. The geometric mean ^{222}Rn levels at different locations range between 4.6 Bq m^{-3} and 147.3 Bq m^{3}. The estimated geometric means of indoor ^{220}Rn levels at these locations range between 3.5 and 42.8 Bq m^{-3}. Fig. 2 shows the lognormal distribution of indoor ^{222}Rn levels at different locations in India, which gives a geometric mean of 23.0 Bq m^{-3} (GSD 2.61). The lognormal distribution pattern of indoor ^{220}Rn levels is shown in Fig. 3 with the geometric mean of 12.2 Bq m^{-3} (GSD 3.22). In view of the large number of measurements carried out, the distributions pattern estimated can confidently be projected as national representations of indoor ^{222}Rn and ^{220}Rn levels in India. The relationship between indoor

^{222}Rn and ^{220}Rn levels is indicated in Fig.4, which shows a good correlation between the two quantities. The relationship indicates that, in general, the indoor thoron concentration is about 50% of that due to indoor ^{222}Rn concentration, which is not trivial as considered earlier. All the data from the present study as well as other relevant data mentioned in this report have been used for preparing the maps of indoor ^{222}Rn and ^{220}Rn concentrations on a national level. Fig. 5 and 6 illustrate these maps of indoor ^{222}Rn and ^{220}Rn levels respectively to represent the different concentration levels.

^{222}Rn level dependencies on different types of dwellings

The variation of indoor ^{222}Rn levels in various types of dwellings is examined using the data and the results are presented in Table 11. A scrutiny of this table reveals that the ^{222}Rn levels are higher in houses constructed with plastered whitewashed walls and mosaic floors. Houses having wooden walls show lowest ^{222}Rn levels. It can be noticed that irrespective of the type of walls, houses constructed with tile flooring show lower ^{222}Rn levels. An analysis has been carried out to evaluate the statistical significance (95% confidence limits) of the difference in means of the indoor ^{222}Rn levels among different dwelling types and the results are given in Table 12. This is based on the assumption that the ^{222}Rn levels follow a normal distribution and that there is not much variation in the ventilation rates in dwellings. Although this analysis does not include all the geographical factors that govern the pattern of radon levels, it provides a general representation for the variation of indoor ^{222}Rn levels in Indian dwellings. Table 12 shows that the differences in the ^{222}Rn levels among different types of floors are small or insignificant when the walls are plastered and painted. This shows that most of the ^{222}Rn emanates from the walls and painted walls will reduce the ^{222}Rn emanation. When the walls are of plastered and whitewash type, there are significant differences between mosaic and any other floor types. Also, whenever mosaic floors are used, the differences are significant between different types of walls. Hence this analysis shows that the combination of whitewash walls and mosaic floors may lead to higher levels of indoor ^{222}Rn. However, the reason for this high ^{222}Rn levels in dwellings having this combination is not obvious from the present set of data. More detailed investigation and categorization are needed in this respect.

Estimation of Ventilation Rates

Several methods such as tracer gas techniques and SSNTD based techniques are being used to estimate the ventilation rates in dwellings. Usual method of determining the ventilation rate in a room involves the measurement of the rate of loss of a tracer gas from the room.

Various tracer gases like CO_2, nitrous oxides and ^{85}Kr are being used for these measurements. The diurnal variations of indoor radon levels also can be used to estimate the ventilation rate in rooms (Ramachandran, 2001; Shaikh et al, 1992). ^{222}Rn and its short-lived progenies, which are naturally present in air, are also being used as a tracer. In the SSNTD based techniques, ^{222}Rn gas and progeny concentrations are estimated in rooms using SSNTD dosimeters in membrane and bare modes of exposure on a time integrated scale. For steady-state ^{222}Rn and its progeny levels, the ratio of the working level (progeny concentration) to ^{222}Rn gas concentration (Bq m^{-3}) is evaluated. This ratio is related to the pseudo-ventilation rate and plate-out rate.

Actual ventilation rate is obtained by subtracting the plate-out rates of attached and unattached fractions of ^{222}Rn daughters from the pseudo-ventilation rates. The ventilation rates estimated by earlier investigations (Shaikh et al, 1992) in Indian dwellings using this method are given in Table 13. The measured ventilation rates varied between 0.42 and 4.46 h^{-1} with a mean of 2.08 h^{-1} (standard deviation of 49%). With respect to the type of dwellings, the ventilation rates varied from 0.42 to 2.82 h^{-1} in Chawls and from 0.52 to 4.46 h^{-1} in flats. This wide variation is acceptable due to differences in construction and atmospheric conditions. Ventilation rates in some other countries like UK and USA range from 0.93 to 2.89 h^{-1} and 0.03 to 1.16 h^{-1} respectively (Nero et al, 1983; Israeli, 1985). Being in the temperate region, Indian dwellings are expected to have higher ventilation rates compared to dwellings in cold regions.

Inhalation Dose Rates

The ^{222}Rn, ^{220}Rn and their progeny concentrations are converted into inhalation dose rates to residents using the above equation and the results are presented in Table 10. This table includes contributions from ^{222}Rn and progeny as well as ^{220}Rn and progeny. The total estimated inhalation dose rates vary from 0.27 m Sv y^{-1} at Kalpakkam to 5.14 m Sv y^{-1} at Digboi with a geometric mean value of 0.97 m Sv y^{-1} (GSD 2.49). Inhalation dose rates due to ^{222}Rn and its progeny show a geometric mean value of 0.63 m Sv y^{-1} (GSD 1.52), while that due to ^{220}Rn and its progeny show a geometric mean value of 034 m Sv y^{-1} (GSD 1.44). It can be seen from this table that the dose due to ^{220}Rn and progeny is about half of that due to ^{222}Rn and progeny. This fact is illustrated in Fig.7, which shows good correlation between the total indoor inhalation dose and that due to ^{220}Rn and its progeny. Contribution of inhalation dose rate due to ^{220}Rn and its progeny is seen to be nearly 17% of the total inhalation dose rate. Nambi et al, (1986) estimated the average external gamma radiation

dose rate in India as 0.80 m Sv y^{-1} based on TLD measurements. These data suggest that in normal background areas, the inhalation dose rates predominate over the external gamma dose rates. The distribution pattern of indoor inhalation dose rates is depicted in Fig.8, which is a lognormal distribution. The majority of measurements indicate that indoor inhalation dose rates range between 0.1 and 2.5 mSv y^{-1}. The geographical variation of indoor inhalation dose rates is also of considerable interest. This information can be used to delineate the normal and high background radiation areas. Though the present survey data is not sufficient for such an exercise, an effort has been made to study the geographical variation of the indoor inhalation dose rates in India is depicted in Fig.9. This figure shows that about 11 locations record dose rates above 1 mSv y^{-1} and most of these locations lie in the northeastern part of the country.

Remedial Action Levels

Elevated levels of indoor ^{222}Rn may be encountered in work places other than uranium or non-uranium mines as well. An issue of concern today is to prescribe action levels (in terms of average indoor levels) above which intervention would be desirable to reduce the levels of human exposure. Action level is defined as the level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situation. Choice of the action level is complex depending not only on the level of exposure but also on the likely scale of action, which has economic implications for the community and for the individuals (IAEA, 1994; ICRP, 1991)**.** ICRP (1993) made a distinction between the existing exposure situations, where any action would have to be remedial, and future situations, which can be subjected to limitation and control at the stage of decision and planning. In this connection, it is pointed out that the distribution pattern of indoor ^{222}Rn follows a lognormal distribution, which means that there would be a very small fraction of the total that would have large values. The geometric mean and geometric standard deviation are appropriate for characterizing this type of distribution. Knowing the geometric mean and geometric standard deviation, it is possible to predict what fraction of the total population would exceed a given value of the parameter. ICRP (1993) has recommended that there is considerable merit in the definition of radon-prone areas so as to focus attention where it is most exigent and on action where it is most effective. A ^{222}Rn prone area may be defined as the one in which about 1% of the buildings has ^{222}Rn concentrations above 200 Bq m^{-3}. The recommended action level is 200 Bq m^{-3} for such a building, which would correspond to an annual effective dose of 5 mSv. On the other hand,

UNSCEAR (1993) recommends an action level of 400 Bq m^{-3}.The international recommendations for ^{222}Rn action levels are given in Table 14 (Sohrabi, 1997)**.** The results presented here, show that the indoor ^{222}Rn levels in India are far below the action levels. Hence, it is clearly demonstrated that most of the dwellings in India do not warrant any action level with respect to indoor ^{222}Rn levels. As per the new WHO recommendations the concentrations levels for ^{222}Rn and ^{220}Rn are 200 and 100 Bq m^{-3}, respectively. But, the study raises some concern about the high inhalation dose rates observed at the northeastern parts of the country.

Conclusions

A countrywide survey on ^{222}Rn and ^{220}Rn levels for India has been carried out in dwellings using Solid State Nuclear Track Detector based passive detector technique. A good database on the total external radiation across the country is supplemented with the inhalation component, which is mainly contributed by ^{222}Rn and ^{220}Rn and their progeny. Calibration factors for the measurements have been derived experimentally as well as theoretically. The results show that the ^{222}Rn gas concentrations at different locations vary between 4.6 and 147.3 Bq $m^{-3}$with an overall geometric mean of 23.0 Bq m^{-3} (GSD 2.61). ^{220}Rn gas concentrations are found to be less than the ^{222}Rn gas concentrations at these locations (3.5 to 42.8 Bq m^{-3}) with an overall geometric mean concentration of 12.2 Bq m^{-3} (GSD 3.22). The inhalation dose rates due to ^{222}Rn, ^{220}Rn and their progeny ranged from 0.27 m Sv yr^{-1} at Kalpakkam to 5.14 m Sv yr^{-1} at Digboi with a geometric mean value of 0.97 m Sv yr^{-1} (GSD 2.49). In general, the indoor ^{220}Rn and progeny concentrations and corresponding inhalation dose rates are found to be about half of that due to ^{222}Rn and its progeny. The geographical distribution pattern shows comparatively high inhalation dose rates (> 2.0 m Sv yr^{-1}) in the northeastern part of India, which is supported by observations of high concentration of uranium, and thorium in soil and rocks in this region. The study also reveals that most of the dwellings in India do not demand any action levels with respect to indoor ^{222}Rn and ^{220}Rn due to good ventilation prevailing in Indian dwellings. However, it raises some concern about the high inhalation dose rates observed in the northeastern part of the country.

References

Barillion R and Chambraudet (2000) Alpha particle dosimetry using solid state nuclear track detectors: Application to radon and its daughters, J Radio-anal and Nucl. Chem, 243, 607 - 620.

Barretto PMC, Clark, Ronald B, and Adams JAS (1972) Physical characteristics of radon-222 emanation from rocks, soils and minerals: its relation to temperature and alpha dose, Natural Radiation Environment II, Conf-720805-P2, USERDA, New York, 731 -740.

Campos-Venuti G, Janssens A and Olast M (1994) Indoor Radon Remedial Action, The Scientific Basis and the Practical Implications, Proceedings of the First International Workshop, Rimini, Italy, Rad. Prot Dos., 56(1-4): 133-135.
discriminating dosimeter, Radiation Measurements 38, 5 – 17

Doi M and Kobayashi, S (1994) The passive radon-thoron discriminative dosimeter for practical use, Hoken Butsuri, 29, 155 - 166.

Doi M, Fugimoto K, Koyabshi S and Yenhara, H (1994) Spatial distribution of thoron and radon concentrations in the indoor air of a traditional Japanese wooden house, Health. Phys, 66, 43 - 49.

Durrani, S A, and Radomir Ilic (1997) Radon Measurements by Etched Track Detectors: Applications in Radiation Protection, Earth Sciences and the Environment, World Scientific, Singapore, 77 - 102.

Eappen KP and Mayya YS (2004) Calibration factors for LR-115 (type-II) based radon thoron

Eappen KP, Ramachandran TV, Shaikh AN and Mayya YS (2001) Calibration factors for SSNTD based radon / thoron dosimeters, Rad. Prot. and Environment. 410 - 414.

Eappen, KP, Ramachandran, TV, Shaikh, AN and Mayya, YS (2001) Calibration factors for SSNTD based radon / thoron dosimeters, Rad. Prot. and Environment, 410 - 414

Fleischer RL, (1997) Radon: Overview of properties, origin and transport, In: Radon Measurements by Etched Track Detectors, Applications in Radiation Protection, earth Sciences and the Environment, (Eds.Durrani, S. A., and Ilic, R), World scientific, Singapore, 1 -20.

Ilic R, and Suteg T (1997) Radon Monitoring devices based on Etched Track Detectors, In: Radon Measurements by Etched Track Detectors, Applications in Radiation Protection, earth Sciences and the Environment, (Eds,, Durrani, S. A., and Ilic, R), World Scientific, Singapore, 103 - 128.

Ingersall JG (1983) A survey of radio nuclide constants and radon emanation rates in building materials used in the US., Health Phys, 45, 363-368.

International Atomic Energy Agency (1994) International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115 - 1, IAEA, Vienna

International Commission for Radiation Protection (1986) Publication No. 50, Lung Cancer Risk from Indoor Exposures to Radon Daughters, Annals of ICRP 16, Pergamon Press, Oxford.

International Commission for Radiation Protection(1993) Publication No. 65, Annals of ICRP 23, Protection Against Rn^{222} at Home and at Work., Pergamon Press, Oxford.

International Commission for Radiation Protection. (1991) Publication No. 60, Recommendations, Pergamon Press, Oxford.

Israeli M (1985) Deposition rates of radon progeny in houses, Health Phys, 49, 1969-1983.

Jacobi W (1993) The history of the radon problems in mines and homes, Annals of the ICRP, 23(2), 39.

Jha G, Raghavayya M, and Padmanabhan N (1982) Radon permeability of some membranes, Rad, Meas., 19, 307 - 308.

Mayya YS, Eappen KP, and Nambi KSV (1998) Methodology for mixed field inhalation dosimetry in monazite areas using a twin-cup dosimeter with three track detectors, Rad. Prot. Dosimetry, 77, 177 - 184.

Megumi K, and Mamuro T, (1974) Emanation and exhalation of radon and thoron gas from soil particles, J. of Geophys. Res., 79(23), 3357-3360.

Menon, MR, Lalit, BY and Shukla, VK (1987) Natural radioactivity content in building construction materials in India, Bull. Rad. Prot, 14, 45 - 48.

Mettler FA and Upton AC (1995) Medical Effects of Ionizing Radiation, 2nd edition, (Eds.) Saunders, W.B. Philadelphia.

Miles JCH (1997) Calibration and standardization of etched track detectors, In Radon measurements by etched track detectors, applications in radiation protection, earth Sciences and the Environment (Eds, Durrani, S. A., and Ilic, R), World Scientific, Singapore, 143-176.

Mishra, UC and Sadasivan, S (1971) Natural radioactivity levels in Indian soil, J. of Sci.and Industrial Research, 30, 59 - 62.

Nambi KSV, Bapat VN, David M, Sundaram VK, Sunta CM, and Soman SD (1986) Natural Background Radiation and Population Dose Distribution in India, BARC Report, Health Physics Division, Bhabha Atomic Research Center, Government of India, Mumbai.

Nambi KSV, Subba Ramu MC, Eappen KP, Ramachandran TV, Muraleedharan TS, and Shaikh AN, (1994) A new SSNTD method for the measurement of radon-thoron mixed working levels in dwellings, Bull. of Rad. Prot., 17, 34 - 35.

Nazaroff WW (1988) Radon and its decay products in indoor air; (Eds. W. W. Nazaroff and A. V. Nero), Chapter 2, John Wiley & Sons, New York, pp. 57 - 112.

Nero AV, Berk JV, Boegel CD, Hollowell JR, Ingersoll, and Nazaroff WW (1983) Radon concentrations and infiltration rates measured in conventional and energy efficient houses, Health Phys, 45,401 - 405.

Nikolaeve VA and Ilic R (1999) Etched track radiometers in radon measurements: A review, Rad Meas., 30, 1-13.

Planinic J and Faj Z (1990) Equilibrium factor and dosimetry of radon with a passive nuclear track etch detector, Rad. Prot. Dosimetry, 1, 97 - 109.

Planinic J and Faj Z (1991) Dosimetry of radon and its daughters by two SSNTD detectors, Rad. Prot. Dosimetry, 35, 265 - 268.

Porstendorfer J (1994) Properties and behavior of radon and thoron and their decay products in the air, J. Aerosol Sci, 25, 219 - 263.

Porstendorfer J and Mercer TT (1979) Influence of electric charge and humidity up on the diffusion coefficient of radon decay products, Health Phys, 37, 191.

Ramachandran TV, Eappen KP, Shaikh AN, and Mayya YS (2001) Indoor radon levels and equilibrium factors in Indian dwellings, Rad. Prot. and Envir, 420-422.

Ramachandran TV, Subba Ramu MC, and Nambi KSV (1995) Simultaneous measurements of radon and its progeny using SSNTDs and evaluation of internal doses due to inhalation, Bull. Rad. Prot., 18, 109 - 114.

Sadasivan S, Shukla VK, Chinnasaki S and Sartandel S J (2003) Natural and fallout radioactivity measurements in Indian soil, J. Radio, Anal. And Nucl. Chem., 256, 603 - 607.

Sankaran AV, Jayswal V, Nambi K S V, and Sunta C M (1986) U,Th and K distributions inferred from region of geology and the terrestrial radiation profiles in India, Bhabha Atomic Research Center (Government of India) Report

Shaikh AN, Muraleedharan TS, Ramachandran TV and Subba Ramu MC (1992) Estimation of ventilation rates in dwellings, The Sci. of the Tot. Envir, 121, 67 - 76.

Sohrabi M (1997) High radon levels in nature and in Dwellings: Remedial actions, In Radon Measurements by Etched Track Detectors, Applications in Radiation Protection, Earth Sciences and the Environment, (Eds. Durrani, S.A., and Ilic, R), World Scientific, Singapore, 225 - 242.

Steinhausler F, Hoffman W, and Lettner H (1994) Thoron exposure to man: A negligible issue? Rad. Prot. Dosi., 56, 1 - 44.

Stranden E, Kolstad AK, and Lind B, (1984) The influence of moisture and Temperature and radon exhalation, Rad. Prot. Dosi., 7, 55-58.

Strong KP, and Levins DM, (1982) Effect of moisture content on radon emanation from uranium ore and tailing, Health Phys, 42, 27.

Subba Ramu MC, Muraleedharan TS, and Ramachandran TV (1988) Assessment of lung dose from radon daughters in dwellings, Rad. Prot. Dosim., 22,187 - 191.

Subba Ramu MC, Raghavayya M, and Paul AC, (1994) Methods for the measurement of radon, thoron and their progeny in dwellings, AERB Technical Manual, TM/RM - 1.

Subba Ramu MC, Ramachandran TV, Muraleedharan TS, Shaikh AN, and Nambi KSV, (1993) Proc. of 7th.Nat. Conf. on Particle Tracks in Solids, Defense Laboratory, Jodhpur, 11 -25.

Tanner AB (1980) Radon migration in the ground: A supplementary review, In proceeding of Natural Radiation Environment III (Eds., Gassel, T. F., and Lowder, W.M), Tech. Infor. Centre, US Department of Energy, Washington, D.C, CONF - 780422.

United Nations Scientific Committee on the Effects of Atomic Radiation (1988) Sources, Effects and Risks of Ionizing Radiation, Report to the General Assembly, United Nations, New York.

United Nations Scientific Committee on the Effect of Atomic Radiation (1992) Sources and Biological Effects, Report to the General Assembly., United Nations, New York.

United Nations Scientific Committee on the Effects of Atomic Radiation (1993) Sources, Effects and Risks of Ionizing Radiation, Report to the GeneralAssembly, United Nations, New York.

United Nations Scientific Committee on the Effect of Atomic Radiation (2000) Sources, Effects and Risks of Ionizing Radiation, Report to the General Assembly, United Nations, New York.

Wafaa A (2002) Permeability of radon-222 through some materials, Rad. Meas., 35, 207 - 211

Ward WJ, Fleischer RL, and Mogro-Campero A (1977) Barrier technique for separate measurement of radon isotopes, Rev. Sci. Instr., 48, 1440 - 1441.

Yihe J, Shimo M, Weihai Z, Liya Xu, and Guoqiu fang (1996) The size distribution of atmospheric radioactive aerosols and its measurement, Proc, of: 4th Int. Conf, on High Levels of Natural Radiation, Beijing, China, October, 21 - 25 (Eds., Luxin, Wei., Tsdtomu, Sugahara., and Zufan, Tao), Elseveir, Amsterdam, 1997, 97 - 109.

Table Caption

Table 1: Natural Radioactivity Content in Indian Building Materials (Menon et al 1987)

Material	^{40}K	^{226}Ra	^{232}Th	Radium equivalent
	Bq kg^{-1}			
Cement	5 - 385	16 - 377	8 - 78	40 - 440
Brick	130 - 1390	21 - 48	26 - 126	88 - 311
Stone	48 - 1479	6 - 155	5 - 412	24 - 311
Sand	5 - 1074	1 - 5047	4 - 2971	22 -7759
Granite	76 - 1380	4 - 98	103 - 240	25 - 525
Clay	6 - 477	7 - 1621	4 - 311	11 -1865
Fly ash	6 - 522	7 - 670	30 - 159	56 - 773
Lime stone	6 - 518	1 - 26	1 - 33	5 - 148
Gypsum	70 - 807	7 - 807	1 - 152	59 - 881

Table 2: Natural Radioactivity Content in Indian soil
(Mishra et al 1971; Sadasivan et al 2003)

Location	^{232}Th	^{226}Ra	^{40}K	Location	^{232}Th	^{226}Ra	^{40}K
	Bq kg^{-1}				Bq kg^{-1}		
Ahmedabad	53.0	24.8	526.6	Kanpur	23.8	24.0	850.9
Aligarh	82.0	54.4	530.1	Kharagpur	18.4	15.2	72.2
Bangalore	16.9	15.2	486.7	Kakrapar	12.4	12.2	94.4
Bhopal	15.7	11.8	376.8	Chennai	23.1	6.7	766.2
Bikanir	11.7	8.8	439.6	Mangalore	13.5	9.3	151.2
Mumbai	13.5	9.4	169.6	Meerut	22.0	22.7	112.3
Kolkatta	24.1	20.4	662.9	Nagpur	16.5	11.8	307.7
Cherrapunji	17.4	21.5	37.7	Nainatal	24.8	24.7	979.7
Chingalput	120.5	22.9	408.2	Nasik	34.4	18.6	290.6
Coimbatore	10.1	10.2	266.9	Ooty	3.4	2.5	87.8
Cuttack	61.7	15.3	722.2	Poona	4.2	3.0	87.9
Darjeeling	24.8	2417	678.2	Ranchi	22.4	24.4	1055.0
Dehradun	22.6	25.9	803.8	Shillong	23.9	15.5	323.2
Delhi	19.9	19.2	536.9	Srinagar	18.6	14.8	615.4
Dhanbad	37.1	53.0	345.4	Tehri	136.2	81.6	328.2
Gangtok	23.9	26.1	854.1	Thiruvalla	74.3	19.8	25.1
Gulmarg	20.1	15.9	555.8	Trivandrum	53.2	20.3	37.7
Hyderabad	45.9	15.2	1073.4	Tiruchirapali	47.8	2070	509.4
Jaduguda	41.0	179.1	455.3	Visakapatnam	24.8	163.2	376.8
Jaipur	14.9	11.6	505.5	Udagamandalam	43.2	114.6	272.6
Jasilmar	37.1	49.0	565.2	Jhansi	12.6	20.4	518.2
Jamnagar	3.8	2.9	56.5	Kaiga	12.4	12.2	94.2
Jodhpur	13.1	10.7	458.9	Thumba	27.5	8.9	-----

Table 3: Uranium, Thorium and Potassium Content in Indian Rocks
(Sankaran et al 1986)

State	^{228}U	^{232}Th	Potassium (%)	^{40}K
	Bq kg^{-1}			
Andaman & Nicobar	31.5	27.4	1.22	378.2
Andhra Pradesh	33.2	40.9	1.65	511.5
Arunachal Pradesh	34.9	98.2	2.00	620.0
Assam	63.0	129.3	2.41	747.1
Bihar	40.9	36.9	1.62	502.2
Daman & Diu	55.7	24.5	1.63	412.3
Delhi	32.6	30.4	1.87	579.7
Goa	33.0	30.5	1.33	412.3
Gujarat	55.7	24.5	1.63	505.3
Haryana	32.6	30.4	1.87	579.7
Himachal Pradesh	32.6	30.4	1.87	579.7
Jammu & Kashmir	43.4	29.0	1.76	545.6
Karnataka*	33.0	30.5	1.33	412.3
Kerala	45.1	47.6	1.80	558.0
Madhya Pradesh	44.0	31.6	1.48	458.8
Maharashtra	31.7	33.4	1.64	508.4
Manipur	95.2	36.2	1.63	505.3
Meghalaya	66.7	32.0	1.67	517.7
Mizoram	35.5	28.8	1.87	579.7
Nagaland	89.1	39.5	2.00	620.0
Orissa	35.4	110.3	1.61	499.1
Pondicherry	27.4	33.1	1.52	471.2
Punjab	32.6	30.4	1.87	579.7
Rajasthan	36.7	32.1	1.64	508.4
Tamil Nadu	27.4	33.1	1.52	471.2
Tripura	33.1	28.5	1.55	480.5
Uttar Pradesh	32.9	33.8	2.03	629.3
West Bengal	47.9	45.1	1.86	576.6

Table 4: Volume Specific Entry Rate and indoor ^{222}Rn Levels from Various Sources (ICRP 1986)

Source	Specific entry rate (Bq m^{-3} h^{-1})		Indoor ^{222}Rn concentration *(Bq m^{-3})	
	Estimated mean	Range	Estimated mean	Range
Brick or concrete	2-20	1-50	3-30	0.7-100
Wooden Houses	< 1	0.05-1	< 1	0.03 - 2
Soil	1-40	0.5-200	2-60	0.5-500
Outdoor air	2-5	0.3-15	3-7	1-10
Others (walls, natural gas)	< 0.1	0.01-10	<0.1	0.01-10
All sources	6-60	2-200	10-1000	2-500

* Mean ventilation rate used is 0.7 h^{-1} (normal range 0.3 – 1.5 h^{-1})

Table 5: Reported Indoor ^{222}Rn Levels Around the World (UNSCEAR 2000)

Region	Country	Concentration (Bq m^{-3})			
		AM	GM	MAX	GSD
Africa	Algeria	30	-	140	-
	Egypt	9	-	24	-
	Ghana	-	-	340	-
North America	Canada	34	14	1720	3.6
	United States	46	25	-	3.1
South America	Argentina	37	26	211	2.2
	Chile	25	-	86	-
	Paraguay	28	-	51	-
East Asia	China	24	20	380	2.2
	Hong Kong	41	-	140	-
	India	57	42	210	2.2
	Indonesia	12	-	120	-
	Japan	16	13	310	1.8
	Kazakhstan	10	-	6000	-
	Malaysia	14	-	20	-
	Pakistan	30	-	83	-
	Thailand	23	16	480	1.2
West Asia	Armenia	104	-	216	1.3
	Iran	82	-	3070	-
	Kuwait	14	6	120	-
	Syria	44	-	520	-
North Europe	Denmark	53	29	600	2.2
	Estonia	120	92	1390	-
	Finland	120	84	20000	2.1
	Lithuania	55	22	1860	-
	Norway	73	40	50000	-
	Sweden	108	56	3900	-
West Europe	Austria	-	15	190	-
	Belgium	48	38	12000	2.0
	France	62	41	4690	2.7
	Germany	50	40	>10000	1.9
	Ireland	-	37	1700	-
	Luxemburg	110	70	2500	2.0
	Netherlands	23	18	380	1.6
	Switzerland	70	50	10000	-
	U.K	20	-	10000	-
East Europe	Bulgaria	-	22	250	-
	Czech Republic	140	-	20000	-
	Hungary	107	82	1990	2.7
	Poland	41	32	432	2.0
	Romania	45	-	1025	-
	Slovakia	87	-	3750	-
South Europe	Albania	120	105	270	2.0
	Croatia	35	32	92	-
	Cyprus	7	7	78	2.6
	Greece	73	52	490	-
	Italy	75	57	1040	2.0
	Portugal	62	45	2700	2.2
	Slovenia	87	60	1330	2.2
	Spain	86	42	15400	3.7
Oceania	Australia	11	8	420	2.1
	New Zealand	20	18	90	-
Median		46	37	480	2.2
Population weighted average		39	30	1200	23

Table 6: Outdoor and Indoor ^{220}Rn Levels around the World (UNSCEAR 2000)

Country	Equilibrium equivalent concentration (Bq m^{-3})		^{220}Rn/^{222}Rn EEC ratio	
	Outdoor	Indoor	Outdoor	Indoor
North America 0.09 United States of America	- (0.03-0.3)	0.5 (0.03-4.7) 0.2 (0.1-0.3)	-	0.04
China	0.4	0.8	0.05	0.07
Hong Kong	0.3 (0.1-0.5)	0.8 (0.4-1.2)	0.04	0.06
Japan	009 (0.03- 0.12)	0.7 (0.04-2.1)	-	0.2
Malaysia	0.5 (0.3-1.8)	1.1 (0.4-2.1)	0.08	0.08
France	-	0.8 (0.6-13.3)	-	0.03
United Kingdom	-	0.3 (0.07-1.1)	-	0.02
Germany	-	0.5 (0.1 -1.0)	-	-
Republic of Moldova	0.2	1.0 (0.1 -6.4)	0.04	0.05
Romania	0.3 (0.1-0.6)	1.1 (0.1-6.4)	0.05	0.04
Russian Federation	-	- (1.1-7 .1)	-	0.09 (0.02 - 0.24)
Italy	-	12 (0.5-76)	-	0.11 (0.01 - 0.38)
Slovenia	0.12 (0.05 - 0.37)	-	0.013	
Range	(0.09 - 0.5)	(0.2 -12)	0.01- 0.08	0.01- 0.5

Table 7: Calibration Factors (CFs) for the Cup Mode and Bare Mode Exposures
(Mayya et al 1998; Eappen et al 2004)

Mode of Exposure	Calibration Factors ($Tr\ cm^{-2}/Bq\ d\ m^{-3}$) for			
	^{222}Rn		^{220}Rn	
	Filter	Membrane	Filter	Membrane
Cup Mode Exposure				
Experimental	0.02 ± 0.004	0.019 ± 0.003	0.017 ± 0.003 0.016	0.0
Theoretical	0.021	-		-
Bare Mode Exposure				
Experimental	0.020 ± 0.002		0.019 ± 0.003	
Theoretical	0.019		0.019	

Table 8: Average concentration of ^{222}Rn, ^{220}Rn and their progeny in air and corresponding annual effective doses (UNSCEAR 2000)

Radionuclide	Location	Concentration ($Bq\ m^{-3}$)		Effective dose equivalent ($mSv/\ Bq\ h\ m^{-3}$)		Annual effective dose (μ Sv)	
		Gas	EEC[+]	Gas	EEC	Gas	EEC
Radon	Outdoor	10	6	0.17	9	3	95
	Indoor	40	16	0.17	9	48	1009
Total							1155
Thoron	Outdoor	10	0.1	0.11	40	2.0	7.0
	Indoor	10	0.3	0.11	40	8.0	84
Total							101
Total Annual Effective Dose Equivalent Due to ^{222}Rn and ^{220}Rn (μ Sv)							1256

[+] This is the equilibrium equivalent concentration (EEC) of radon/thoron and is the product of the concentration of radon/thoron and the equilibrium factor between radon/ thoron and its decay products. The equilibrium factor has been taken as 0.6 for outdoor and 0.4 for indoor in the case of radon. In the case of thoron F is taken as 0.01 for outdoor and 0.03 for indoor. These values are weighted for an occupancy factor of 0.2 for outdoor and 0.8 for indoor.

Table 9: Indoor ^{222}Rn levels and equilibrium factors in Indian dwellings using Cup dosimeter (Ramachandran et al 1995)

State	Sites	No. of houses	Radon levels (Bq m^{-3})				Equilibrium factor			
			MAX	MIN	GM	GSD	MAX	MIN	GM	GSD
Andhra Pradesh	5	5	41.8	6.4	17.5	1.7	0.93	0.27	0.46	1.4
A & Nicobar	1	1	15.6	10.0	13.4	1.2	0.58	0.46	0.51	1.1
Arunachal Pradesh	1	1	27.6	16.9	20.6	1.2	0.35	0.24	0.29	1.2
Assam	2	5	88.7	43.7	67.6	1.1	0.87	0.48	0.67	1.1
Bihar	9	15	92.6	7.4	40.9	1.9	0.92	0.32	0.61	1.2
Chaidigarh	1	1	29.9	19.3	25.6	1.2	0.42	0.33	0.36	1.1
Delhi	1	1	39.8	12.7	18.4	1.4	0.90	0.36	0.59	1.4
Ooa	1	1	23.4	8.8	15.5	1.4	0.59	0.42	0.53	1.2
Gujarath	3	3	26.4	9.4	15.0	1.4	0.94	0.39	0.65	1.3
Haryana	2	4	96.8	7.0	32.1	2.6	0.85	0.36	0.54	1.4
Himachal Pradesh	3	3	43.6	10.4	18.3	1.4	0.80	0.36	0.57	1.3
Karnataka	6	6	56.9	16.7	14.9	1.6	0.86	0.29	0.46	1.4
Kerala	9	9	51.3	7.1	17.0	1.6	0.95	0.21	0.51	1.5
Maharashtra	5	5	35.2	7.6	21.2	1.4	0.88	0.30	0.48	1.3
Madhya Pradesh	2	2	45.8	12.2	21.3	1.5	0.67	0.32	0.44	1.3
Meghalaya	2	2	33.7	11.6	17.3	1.4	0.92	0.30	0.48	1.5
Orissa	3	12	64.8	14.6	30.1	1.6	0.67	0.21	0.42	1.4
Punjab	4	4	93.0	9.0	44.7	2.2	0.87	0.30	0.55	1.4
Pondicheery	1	1	14.2	6.9	9.9	1.3	0.63	0.42	0.48	1.2
Rajashtan	2	2	66.9	7.9	21.4	2.3	0.77	0.26	0.44	1.5
Sikkim	1	1	55.9	25.1	38.3	1.3	0.34	0.31	0.32	1.0
Tripura	I	1	59.3	25.1	40.0	1.5	0.59	0.28	0.41	1.3
Tamil Nadu	11	11	51.9	5.9	15.3	1.7	0.75	0.20	0.44	1.3
Uttar Pradesh	6	6	95.4	10.5	27.0	1.8	0.81	0.31	0.54	1.3
West Bengal	3	3	95.4	6.4	25.5	2.1	0.95	0.21	0.54	1.4

Table 10: Indoor ^{222}Rn, ^{220}Rn levels and Inhalation Doses

No	Location	No. of Houses	^{222}Rn (Bq m^{-3})		^{220}Rn (Bq m^{-3})		Inhalation dose (mSv y^{-1})		Total inhalation Dose (mSv y^{-1})
			GM	GSD	GM	GSD	^{222}Rn + Progeny	^{220}Rn + Progeny	
01	Patiala	91	11.2	2.2	6.3	2.7	0.37	0.07	0.44
02	Chandigarh	40	15.9	1.7	8.4	2.4	0.53	0.10	0.63
03	Palanpur	30	29.2	1.7	14.6	2.4	0.96	0.17	1.13
04	Amritsar	70	14.0	2.0	7.8	2.7	0.46	0.09	0.55
05	Hamirpur	29	48.8	1.8	32.3	2.4	1.61	0.37	1.98
06	Tehri	121	41.6	1.7	13.1	2.2	1.37	0.15	1.52
07	Kumaun Hill	68	18.9	1.5	21.1	2.1	0.62	0.24	0.86
08	Hyderabad	72	4.6	2.1	3.5	3.3	0.15	0.04	0.19
09	Secunderabad	80	48.5	2.1	34.0	3.3	1.60	0.39	1.99
10	Chennai	100	14.3	2.3	6.4	3.3	0.48	0.08	0.55
11	Chennai suburbs	113	15.1	1.7	13.5	2.1	0.50	0.16	0.66
12	Kalpakkam	42	6.3	1.8	5.7	1.9	0.21	0.07	0.28
13	Mysore	70	21.5	2.7	19.6	3.1	0.71	0.23	0.94
14	Mysore surburbs	106	9.7	2.7	11.4	3.1	0.32	0.13	0.45
15	Kamptee	12	8.7	2.3	6.1	2.9	0.29	0.07	0.36
16	Nagpur	84	54.3	3.3	15.1	4.2	1.79	0.17	1.96
17	Guwahati	48	48.1	1.7	25.4	1.7	1.59	0.29	1.88
18	Shillong	29	59.7	2.0	29.5	2.1	1.97	0.34	2.31
19	Karimganj	7	37.6	1.5	10.2	1.7	1.24	0.12	1.36
20	Kailash sahar	5	31.3	1.6	15.5	1.9	1.03	0.18	1.21
21	Itanagar	65	41.1	1.7	28.6	1.8	1.36	0.33	1.69
22	Mizoram	17	27.6	1.7	12.1	2.0	0.91	0.14	1.05
23	Namrup	10	147.3	1.4	23.6	2.1	4.87	0.27	5.14
24	Digboi	20	60.5	1.7	42.8	2.3	1.15	0.21	1.36
25	Agarthala	57	34.7	1.7	18.3	2.1	0.21	0.07	0.28
Mean ^{222}Rn concentration (Bq m^{-3})									23.0
Mean ^{220}Rn concentration (Bq m^{-3})									12.2
Mean total inhalation dose rate (mSv y^{-1})									0.97

Table 11: ^{222}Rn levels in different types of dwellings

Wall Type	Flooring	No. of houses	GM (AM) (Bq m^{-3})	GSD(SD)
Bare	Cement	4	20.8 (21.6)	1.3 (7.0)
Plaster and painted	Cement	121	20.2 (23.4)	1.7 (13.2)
	Mosaic	95	18.1(21.4)	1.8 (13.2)
	Tile	12	12.9(13.5)	1.4 (4.0)
White washed	Stone	1	28.5 (28.5)	1.0 (0.0)
	Cement	11	15.1 (18.5)	1.8 (14.9)
	Mosaic	7	34.8 (38.9)	1.7 (18.0)
	Wood	4	15.4(17.8)	1.7 (11.9)
	Tile	4	12.1 (13.0)	1.5 (4.8)
Wooden panel	Cement	3	10.8 (10.9)	1.1 (1.4)
	Mosaic	8	13.7(13.9)	1.2 (2.9)

Table 12: Statistical significance between radon level and type of dwelling

Wall	Floor	Difference of means	Statistical estimate	95 % Confidence limits	Remarks
Plaster and paint	Cement	2.00	2.30	-2.5 to 6.5	No difference
	Mosaic				
	Cement	9.90	1.66	6.7 to 13.8	Small difference
	Tile				
	Mosaic	7.90	2.28	3.4 to 12.3	Small difference
	Tile				
Plaster and whitewash	Mosaic	20.40	8.15	4.1 to 36.4	Significant difference
	Cement				
	Cement	5.50	5.09	-4.5 to 15.5	No difference
	Tile				
	Mosaic	21.10	9.04	3.4 to 38.3	Significant difference
	Wood				
	Mosaic	25.90	7.21	11.8 to 40.0	Significant difference
	Tile				
	Wood	4.80	6.42	-7.8 to 17.4	No difference
	Tile				
Wood	Mosaic	3.00	1.31	0.4 to 5.6	Small difference
	Cement				
Floor	Wall	Difference of means	Statistical estimate	95 % Confidence limits	Remarks
Cement	Plaster/paint	4.90	4.65	-4.2 to 14.0	No difference
	Plaster/whitewash				
Mosaic floor	Plaster/whitewash	17.50	7.08	3.6 to 37.4	Significant difference
	Plaster/paint				
	Plaster/whitewash	25.00	6.89	11.5 to 38.5	Significant difference
	Wood				

Table 13: Ventilation Rates in Indian Dwellings (Shaikh et al 1992)

Type of dwelling	Pseudo ventilation Rate (h^{-1})	Plate out rate (h^{-1})	Actual ventilation rate (h^{-1})	* Mean ventilation rate (h^{-1})
Chawl	3.9	1.43	2.43	1.73
	2.4	1.07	1.33	
	1.5	1.10	0.42	
	3.7	0.90	2.82	
	3.7	1.43	2.27	
	2.1	1.02	1.08	
Bungalow	5.0	1.38	3.62	2.76
	4.5	2.61	1.89	
A/C room	4.7	2.73	1.97	2.14
	4.9	2.59	2.31	
Flat	3.0	1.02	1.98	2.15
	2.5	1.98	0.52	
	3.6	1.45	2.15	
	6.7	2.24	4.46	
	3.3	1.69	1.61	
	2.8	1.76	1.04	
	5.5	2.08	3.42	
	3.7	1.65	2.05	

Table 14: Action Levels Reported in Literature (Soharabi, 1997)

Country	Action Level (Bq m^{-3})		**Remarks and/or recommended time for remedial action**
	Old Building	New Building	
Australia	200	200	…..
Austria	400	400	…….
Canada	800		…….
Denmark	200	200	…….
Germany	250	250	A time frame band and on the basis of a life time (60 y) cumulative exposure of 15,000 Bq/m^3 y; 10 times higher than the UK (NRPB) level
Ireland	200	200	
Sweden	200	70	Between 70 to 200 should be reduced by simple measurements if possible
United Kingdom	200	200	A time frame band on the basis of a life time (60 **y)** cumulative exposure of 1500 Bq/m^3 , a few years; for 750 to 7500 Bq/m^3, within a few months; above 7500 Bq/m^3, immediate action or evacuation.
United States	150	150	
ICRP 65	200-600	200-600	
IAEA-BSS	200-600	200-600	
CEC	400	200	
WHO	200-300	200-300	

Figure Caption

Fig. 1: Frequency distribution of equilibrium factors

Fig. 2: Distribution pattern of indoor ^{222}Rn levels

Fig. 3: Distribution pattern of indoor ^{220}Rn levels

Fig. 4: Relation between indoor ^{222}Rn and ^{220}Rn concentrations

Fig. 5: Indoor ^{222}Rn levels in India

Fig. 6: Indoor ^{220}Rn levels in India

Fig. 7: Relation between total indoor inhalation dose rates and that due to ^{220}Rn and its progeny

Fig. 8: Distribution pattern of total indoor inhalation dose rates

Fig. 9: Total indoor inhalation dose rates due to ^{222}Rn, ^{220}Rn and their progeny at different locations in India

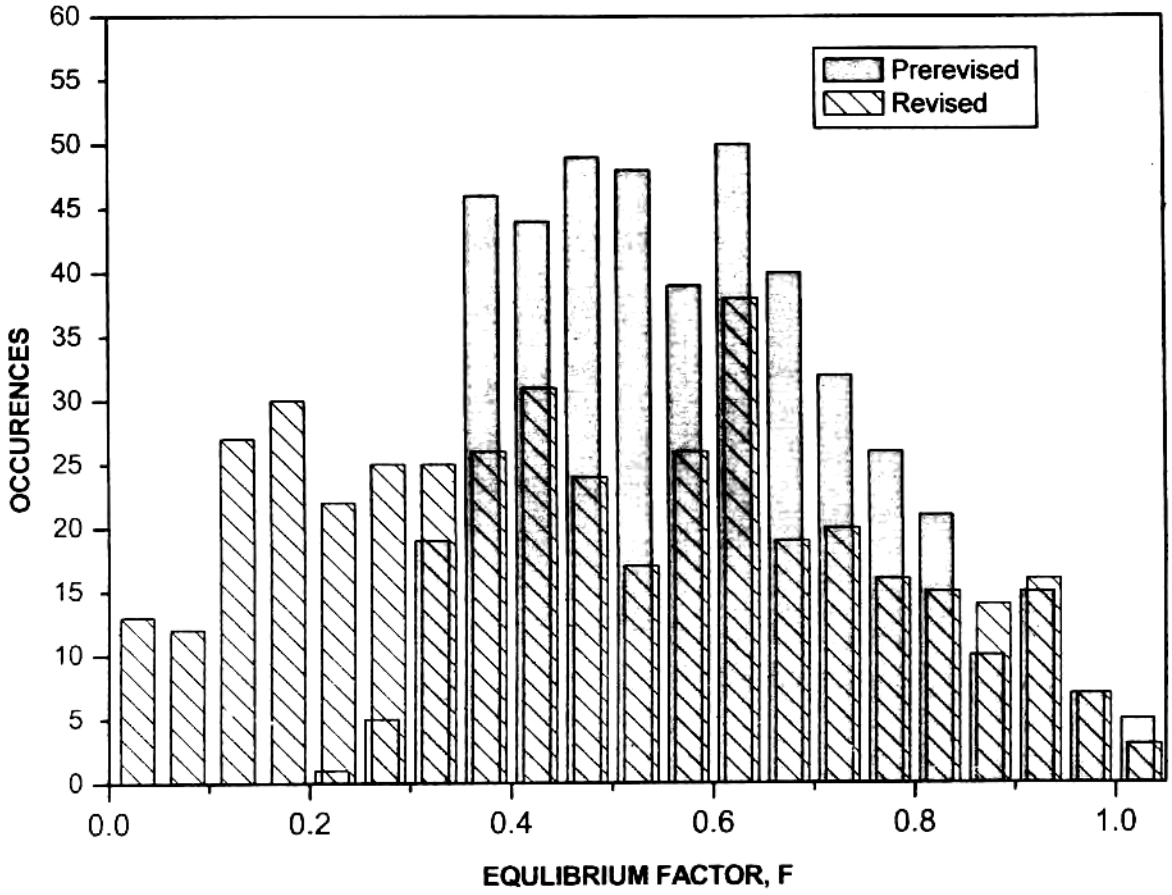

Fig. 1: Frequency distribution of equilibrium factors

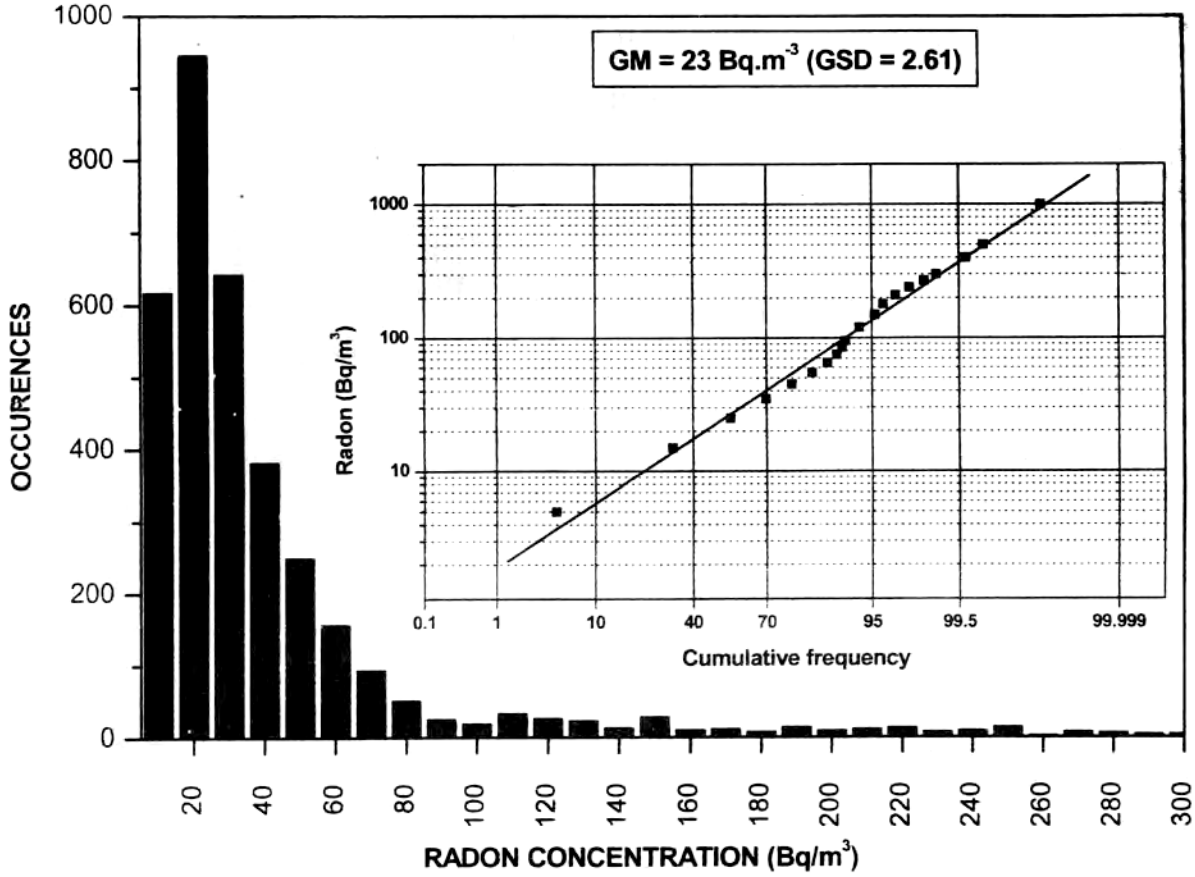

Fig. 2: Distribution pattern of indoor ^{222}Rn levels

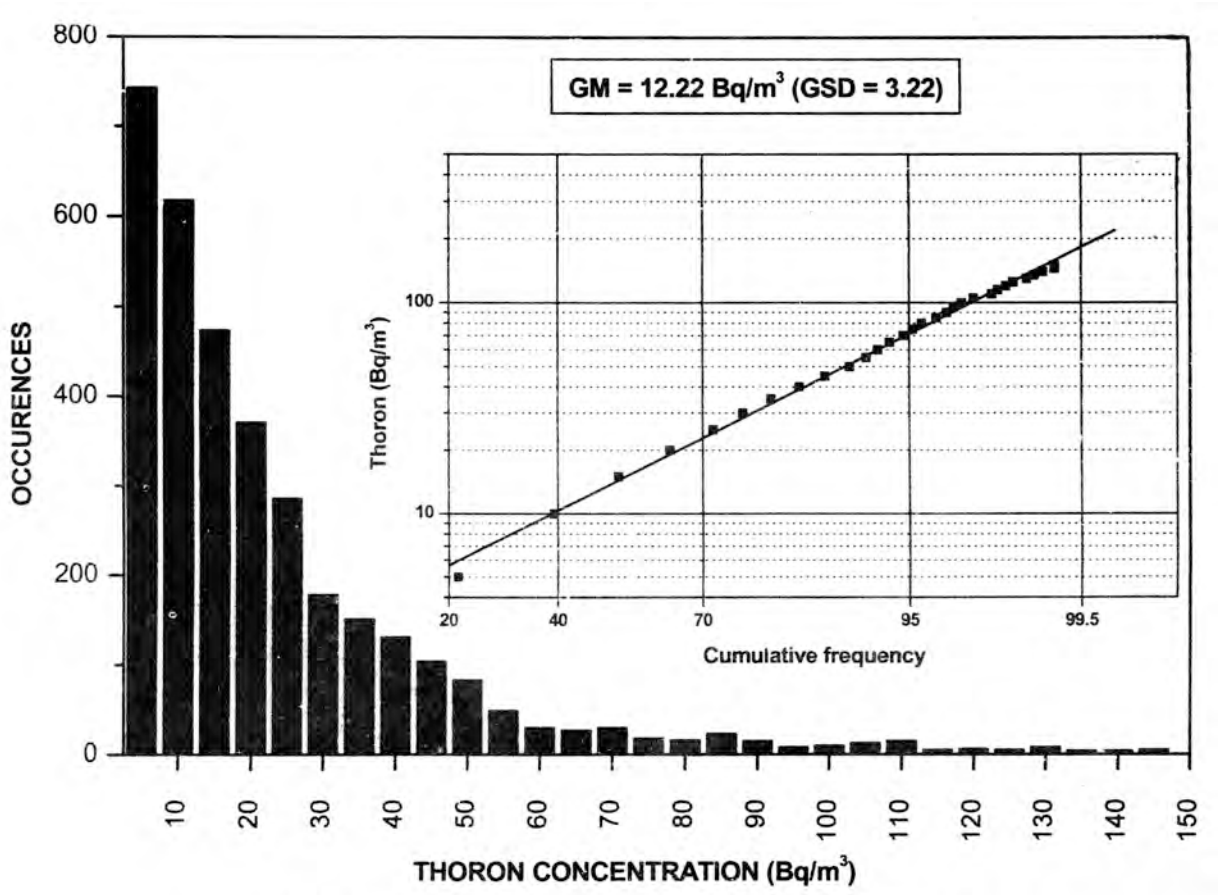

Fig. 3: Distribution pattern of indoor ^{220}Rn levels

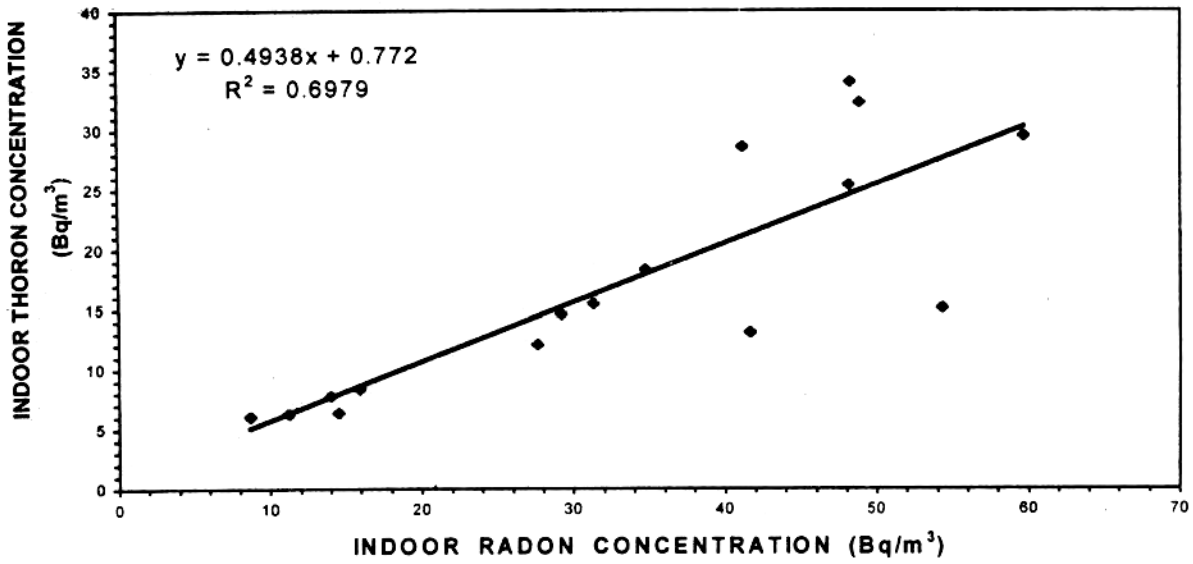

Fig. 4: Relation between indoor ^{222}Rn and ^{220}Rn concentrations

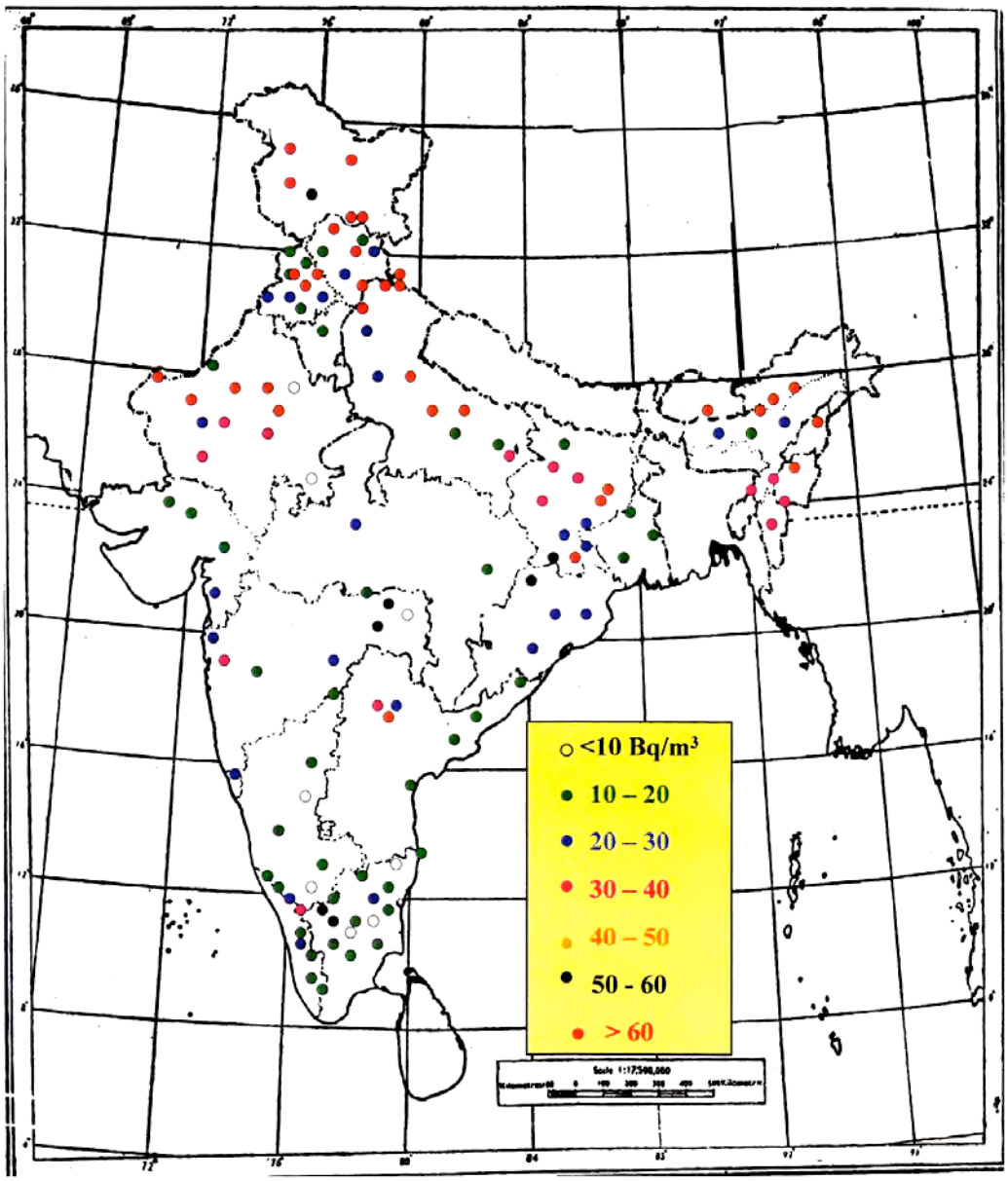

Fig. 5: Indoor ^{222}Rn levels in India

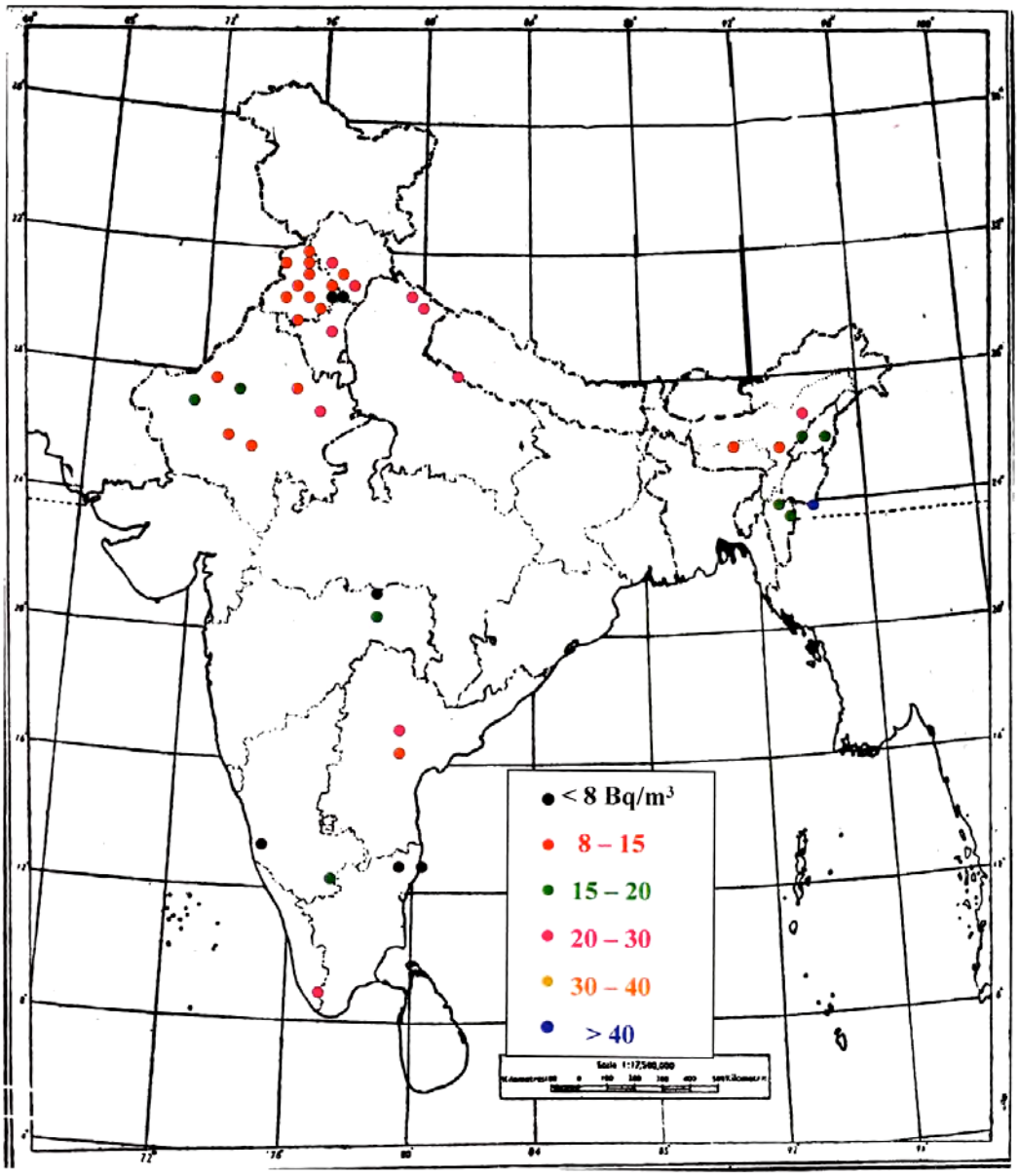

Fig. 6: Indoor ^{220}Rn levels in India

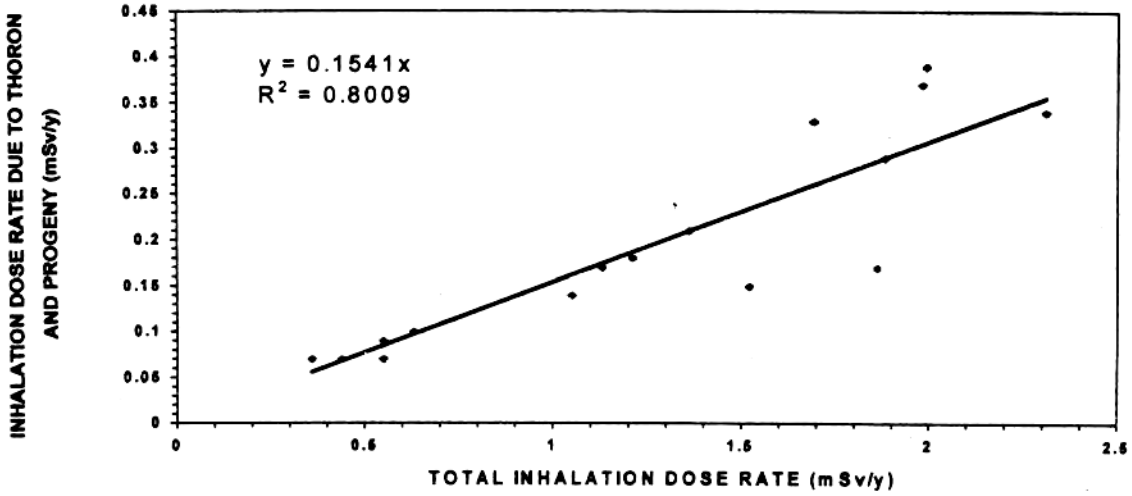

Fig. 7: Relation between total indoor inhalation dose rates and that due to ^{220}Rn and its progeny

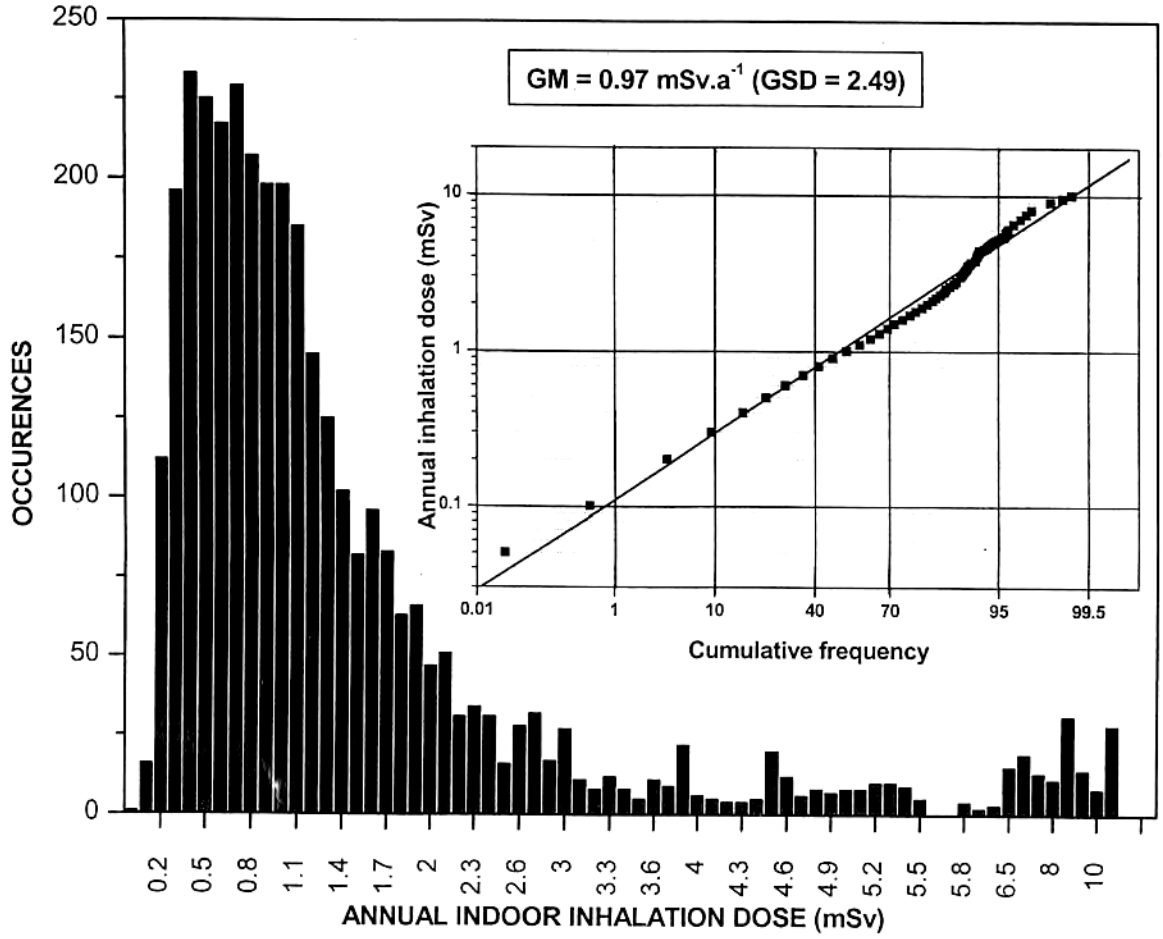

Fig. 8: Distribution pattern of total indoor inhalation dose rates

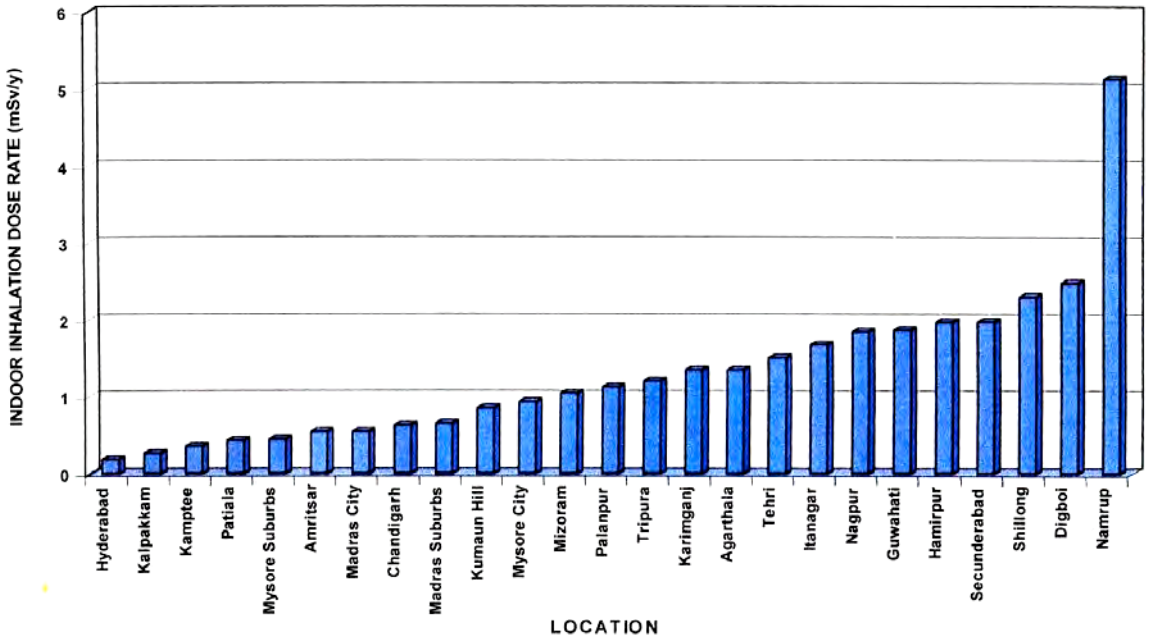

Fig. 9: Total indoor inhalation dose rates due to ^{222}Rn, ^{220}Rn and their progeny at different locations in India